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Short communication

The accuracy of the Oculus Rift virtual reality head-mounted display during cervical spine mobility measurement

Xu Xu [a,*], Karen B. Chen [b], Jia-Hua Lin [c], Robert G. Radwin [d]

[a] Liberty Mutual Research Institute for Safety, 71 Frankland Road, Hopkinton, MA 01748, USA
[b] Department of Biomedical Engineering, University of Wisconsin-Madison, Madison, WI 53706, USA
[c] Safety & Health Assessment & Research for Prevention (SHARP) Program, Washington State Department of Labor and Industries, P.O. Box 44330, Olympia, WA 98504, USA
[d] Department of Industrial and Systems Engineering, University of Wisconsin-Madison, Madison, WI 53706, USA

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ABSTRACT

An inertial sensor-embedded virtual reality (VR) head-mounted display, the Oculus Rift (the Rift), monitors head movement so the content displayed can be updated accordingly. While the Rift may have potential use in cervical spine biomechanics studies, its accuracy in terms of cervical spine mobility measurement has not yet been validated. In the current study, a VR environment was designed to guide participants to perform prescribed neck movements. The cervical spine kinematics was measured by both the Rift and a reference motion tracking system. Comparison of the kinematics data between the Rift and the tracking system indicated that the Rift can provide good estimates on full range of motion (from one side to the other side) during the performed task. Because of inertial sensor drifting, the unilateral range of motion (from one side to neutral posture) derived from the Rift is more erroneous. The root-mean-square errors over a 1-min task were within 10° for each rotation axis. The error analysis further indicated that the inertial sensor drifted approximately 6° at the beginning of a trial during the initialization. This needs to be addressed when using the Rift in order to more accurately measure cervical spine kinematics. It is suggested that the front cover of the Rift should be aligned against a vertical plane during its initialization.

1. Introduction

Oculus VR (Irvine, CA) introduced an inexpensive 3-D virtual reality (VR) head-mounted display (HMD), the Oculus Rift (the Rift), in late 2012. The Rift embeds a 3-D inertial sensor (IS) and uses a customized algorithm developed by Oculus VR to track and monitor head movement so the content displayed can be compensated in an immersive VR environment (Parkin, 2014). Although the Rift was originally designed for the gaming industry, researchers have recently explored the possibility of using it in research areas such as rehabilitation (Chen et al., 2014) and pain distraction (Hoffman et al., 2014). In Chen et al. (2014), a VR rehabilitative system incorporating the Rift was used to detect cervical spine mobility and facilitate those with kinesiophobia.

While the Rift may have great potential for cervical spine biomechanics studies, its accuracy in terms of cervical spine mobility measurement is yet to be validated. Previous studies have used various applications of inertial sensors in biomechanics studies, including rehabilitation and fall assessment (Lockhart et al., 2012; Perez et al., 2010). It was found that inertial sensors attached on body segments can provide an approximate assessment of upper and lower extremity kinematics (Cutti et al., 2008; Favre et al., 2006). Specifically, placing inertial sensors on clinically identifiable positions, such as one on the head and one on the trunk, can provide good estimates on cervical spine mobility (Duc et al., 2014; Theobald et al., 2012). A very recent study (Cuesta-Vargas and Williams, 2014) also placed inertial sensors on the head to facilitate cervical spine manipulation during physiotherapy. Nevertheless, using the Rift to measure cervical spine mobility relies on one single inertial sensor mounted in the Rift, as well as the algorithms developed by Oculus VR for deriving real-time orientation of the Rift in game playing. The goal of the current study is to (1) examine the accuracy level of the Oculus Rift during cervical spine movement and (2) to investigate the amount of error contributed by different error sources.

2. Method

Ten participants, three males and seven females, height: 171 (SD=11) cm, age: 44.9 (SD=23.5) years, and free of acute or chronic neck pain were recruited from the local community. Written informed consent was obtained for a protocol approved by the local Institutional Review Board. After being seated in a back-supported chair with the Rift mounted comfortably and securely on the participant's head, a one-minute head movement task in the VR environment was performed. At the beginning of the

* Corresponding author. Tel.: +1 508 497 0218.
E-mail address: Xu.Xu@libertymutual.com (X. Xu).

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experimental task, the Rift was initialized and the inertial sensor was reset. The output of the inertial sensor was relative to its orientation at the instant of the reset.

The VR environment scenario contained images of a yellow field goal post and a football. The field goal post was fixed in front of the viewpoint of the participant and it moved corresponding to the participant's gaze relative to the background during head movement. The football was stationary to the background and it appeared at one of the nine random locations (Fig. 1a). Participants were instructed to align the field goal with the football using head movement (Fig. 1b). The locations in Fig. 1 were pre-determined within 80% of the mean neck range of motion (RoM) in head axial rotation and flexion/extension (Chiu and Lo, 2002; Piva et al., 2006).

An active-marker infrared motion tracking system (Optotrak Certus System, Northern Digital, Canada), with an accuracy level of 0.1 mm, was used as the 3-D kinematics ground truth measure of the trunk, head, and the Rift. Clusters of three markers were attached on the trunk and the Rift. Anatomical landmarks including the sternal notch, xiphoid process, C7, T8, left and right tragion, and vertex, as well as the four corners of the Rift, were digitized with participants wearing it in an upright-seated reference posture before the start of the task. The local coordinate system of the trunk was constructed according to the ISB recommendations (Wu et al., 2005). The head *Z*-axis was from the left tragion to the right tragion, and the *X*-axis was perpendicular to the plane including the *Z*-axis and the vertex pointing forward. The Rift *X*-axis was perpendicular to the front cover pointing forward, and the *Z*-axis was from the lower left corner to the lower right corner. During the neutral posture, for trunk, head and the Rift, the *X*-axis pointed forward, the *Y*-axis pointed upward, and the *Z*-axis pointed laterally to the right side (Fig. 1a). The Rift and the motion tracking system were synchronized at a 60 Hz sample rate.

The Rift-based neck lateral bending, axial rotation, and flexion/extension were extracted using *Y*–*X*–*Z* Euler angle sequence from ${}^{IS(tr)}\mathbf{R}^{IS(t)}$, which is the orientation of the inertial sensor at time t relative to its orientation at the time of resetting the inertial sensor at the beginning of the task (t_r). The reference neck kinematics were extracted using the same Euler angle sequence from ${}^{T(t)}\mathbf{R}^{H(t)}$, which is the orientation of the head relative to the trunk. In order to examine the measurement accuracy of the Rift, RoM derived from both the Rift and the infrared motion tracking system was calculated, as well as the error during the maximum rotation and the root-mean-square error (RMSE) of the Rift.

In addition, an error analysis was performed to understand the error attributed by various error sources. ${}^{IS(tr)}\mathbf{R}^{IS(t)}$ and ${}^{T(t)}\mathbf{R}^{H(t)}$ are associated based on the following equation:

$${}^{T(t)}\mathbf{R}^{T(t_r)} \cdot {}^{T(tr)}\mathbf{R}^{Go(t_r)} \cdot {}^{Go(tr)}\mathbf{R}^{IS(t_r)} \cdot {}^{IS(tr)}\mathbf{R}^{IS(t)} \cdot {}^{IS(t)}\mathbf{R}^{Go(t)} \cdot {}^{Go(t)}\mathbf{R}^{H(t)} = {}^{T(t)}\mathbf{R}^{H(t)}$$

in which

1. ${}^{T(t)}\mathbf{R}^{T(t_r)}$ is the orientation of the trunk at time t relative the orientation at time t_r, and it represents the error introduced by trunk movement during head movement,
2. ${}^{T(tr)}\mathbf{R}^{Go(t_r)}$ is the motion tracking system-based orientation of the Rift relative to the trunk at time t_r, and it represents the error due to the initial misalignment between the Rift and the trunk,
3. ${}^{Go(tr)}\mathbf{R}^{IS(t_r)}$ is the orientation of the Rift relative to the inertial sensor at time t_r, which is assumed to be an identity matrix in the current study since the inertial sensor is well aligned with the front cover of the Rift,
4. ${}^{IS(t)}\mathbf{R}^{Go(t)}$ is the orientation of the inertial sensor relative to the Rift at time t, which represents the drift error of the inertial sensor,
5. ${}^{Go(t)}\mathbf{R}^{H(t)}$ is the orientation of the goggles relative to the head at time t, which represents the error due to the initial misalignment between the Rift and the head.

To quantify the error introduced by ${}^{T(tr)}\mathbf{R}^{Go(t_r)}$, ${}^{IS(t)}\mathbf{R}^{Go(t)}$, and ${}^{Go(t)}\mathbf{R}^{H(t)}$, the trace of each rotation matrix and the corresponding angle difference, $\arccos(\mathrm{trace}(\mathbf{R})-1/2)$, were calculated. A trace equal to 3 indicates an exact match between two coordinate systems. For each participant, the traces of ${}^{T(tr)}\mathbf{R}^{Go(t_r)}$ and ${}^{Go(t)}\mathbf{R}^{H(t)}$ are constant numbers, while the traces of ${}^{T(t)}\mathbf{R}^{T(t_r)}$ and ${}^{IS(t)}\mathbf{R}^{Go(t)}$ change over time.

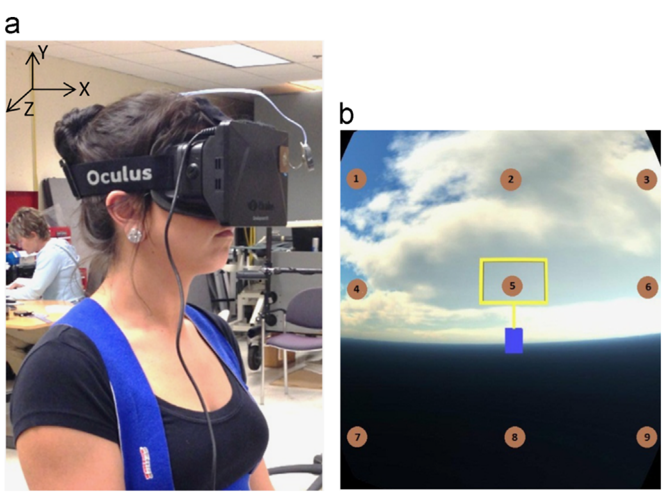

Fig. 1. (a) A participant wearing the Oculus Rift performing the task. The marker cluster on the trunk is obstructed in this photo as it was placed at the mid-thoracic level around T6 and secured via a customized harness. The coordinate system represents the head and trunk coordinate systems during the neutral posture. (b) A yellow field goal post at the center viewpoint of the participant. The brown circles labeled 1–9 depict the positions of the nine pre-determined locations of the football. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results

Across all participants, the average Rift-based full RoM (from one side to the other side) was close to that measured by the reference motion tracking system (Table 1). The absolute error of the Rift-based full RoM was 5.4°, 3.7°, and 2.3° for lateral bending, axial rotation, and flexion/extension, respectively. The average error of the unilateral maximum cervical spine movement (from one side to the neutral posture) across all the participants during the performed task was within $\pm 5°$, however, with a large inter-participant variance (Table 1). The RMSE errors for each rotation axis were all within 10°.

The average traces of ${}^{T(tr)}\mathbf{R}^{Go(t_r)}$ and ${}^{Go(t)}\mathbf{R}^{H(t)}$ across all the participants were 2.97 (0.03) and 2.98 (0.02), respectively. The corresponding angles were 9.3° (4.6°) and 7.6° (3.4°), correspondingly. The average trace of ${}^{T(t)}\mathbf{R}^{T(t_r)}$ over time showed that the trunk slightly moved over time, and the average trace of ${}^{IS(t)}\mathbf{R}^{Go(t)}$ over time indicated that there was an error associated with drifting from the inertial sensor (Fig. 2a and b).

4. Discussion

The current study aims to examine the level of accuracy of the Oculus Rift during cervical spine movement, as well as to investigate the amount of error contributed by different error sources. Overall, the results indicate that using the Oculus Rift to measure cervical spine mobility during the task performed in this study could provide an approximate estimate of the RoM of lateral bending, axial rotation and flexion/extension. However, the measurement error of unilateral RoM can be greater than the error of the full RoM (Table 1). This is mainly related to the drifting error of the inertial sensor as well as the movement of the trunk during the task. While

Table 1
RoM derived from both systems, error during the maximum rotation and the root-mean-square error (RMSE). The number in the parentheses represents one standard deviation.

		Lateral bending	Axial rotation	Flexion/extension
RoM (deg)	Motion tracking	18.6 (7.2)	97.3 (3.7)	70.0 (9.1)
	the Rift	16.2 (3.6)	99.5 (5.9)	69.8 (7.7)
Error during the maximum RoM in the task (deg)		−4.4 (4.3) (left)	3.0 (7.0) (left)	−2.4 (9.6) (ext)
		3.6 (4.4) (right)	2.5 (4.9) (right)	−1.9 (10.9) (flex)
RMSE (deg)		3.9 (2.1)	6.6 (4.5)	9.5 (3.9)

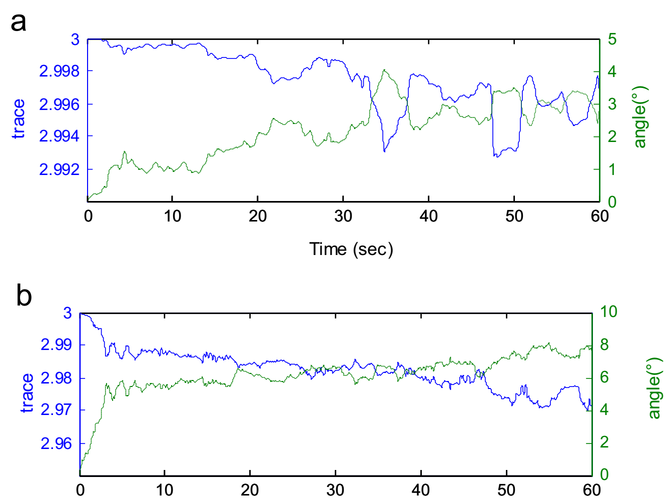

Fig. 2. (a) The average trace of ${}^{T(t)}\mathbf{R}_{T(t_r)}$ over time (solid line, left axis) and the corresponding angle difference (dashed line, right axis). (b) The average trace of ${}^{IS(t)}\mathbf{R}_{Go(t)}$ over time and the corresponding angle difference.

such error sources exist, in the case of one side RoM being over/underestimated and the other side RoM being under/overestimated, and then the entire RoM could be less affected.

The average trace of ${}^{IS(t)}\mathbf{R}^{Go(t)}$ over time showed a prominent drift for approximately 6° in the first 3 s at the beginning of a trial. The drift over the rest of the time until the end of a trial was approximately 2°. As the Rift was designed to deliver a VR environment to gamers, it is important that the content displayed in the Rift and the Rift both share the same orientation in the global coordinate system of the physical environment. In order to achieve that, the Rift artificially drifts the orientation of the inertial sensor to eliminate the accelerometer-based tilting angle in the few seconds after the initialization of the Rift (LaValle, 2013). However, this feature may positively or negatively impact the measured cervical spine kinematics. When the trunk and the head are well aligned along the vertical *y*-axis, this artificial drift can be helpful in correcting the error due to the initial misalignment between the Rift and the head, and the orientation of the inertial sensor at time *t* should be calculated relative to the time that the artificial drift has ceased. If the trunk and the head cannot be vertically aligned, such as when a user lies on an incline, this feature could introduce more errors to cervical spine kinematics. It should be noted that the advantage of the Rift is to provide an affordable immersive VR environment for the gaming industry, and the provided customized algorithm to track the goggles movement is not necessarily optimized for monitoring cervical spine mobility. If a VR environment is not included in a study, one can use multiple inertial sensors and functional calibrations to derive a better accuracy for cervical spine measurement, as proposed by Duc et al. (2014).

There was minimal trunk movement involved in this study (Fig. 2a). It should be noted, however, that the task performed in the VR environment did not require the participants to move their head to an extreme posture since it was designed based on 80% of the mean neck RoM. During the full RoM movement, the trunk is more likely to move and the movement of the trunk can contribute more errors to the Rift-based cervical spine kinematics. In addition, each task was only performed for 1 min. For a longer duration of data collection, the cumulative trunk movement could be greater and result in more error. Therefore, the trunk orientation needs to be well fixed during the data collection to improve the accuracy of the Rift-based cervical spine kinematics.

The trace of ${}^{T(tr)}\mathbf{R}^{Go(t_r)}$ and ${}^{Go(t)}\mathbf{R}^{H(t)}$ indicates that there were some misalignments between the Rift and the trunk at the beginning of the task, and between the Rift and the head. Further analysis indicates that between the Rift and the trunk, the Rift deviated from the trunk coordinate system by 1.7° (3.1°) in lateral bending, 1.0° (6.5°) in axial rotation, and 0.0° (8.2°) in flexion/extension. This suggests that the misalignment between the Rift and the trunk at the beginning of the task varied between individuals but was unbiased over all the participants. Between the Rift and the head, the Rift deviated from the head coordinate system by 0.8° (2.2°) in lateral bending, 0.8° (2.4°) in axial rotation, and −5.9° (5.2°) in flexion/extension. Such results suggest that, compared with the head coordinate system, the Rift flexed down for most of the participants. This is possibly because the Rift sometimes was slightly flexed down when mounting it on the head in order to have a more secure contact with the floor of the orbits.

There are some limitations that need to be addressed. First, the task performed in the current study only involved moderate head movement. Given that the inertial sensor error is influenced by the magnitude of angular velocity (Guo and Zhong, 2013), the accuracy level of using the Rift to measure cervical spine mobility can be altered when the head movement is more drastic. Second, due to the moderate head movement, it was assumed that the head and the Rift moved together, and the marker clusters placed on the Rift was used to track the movements of the head and the Rift. With a more drastic head movement, relative movement between the head and the Rift can be expected, which would introduce additional error to the measurement of cervical spine mobility. Third, the current study used the head movement relative to the trunk to represent cervical spine mobility. The orientation of each cervical spine vertebra, however, remains unclear.

In conclusion, when using the Oculus Rift to measure cervical spine kinematics, it is recommended that the head and trunk be vertically aligned, that the front cover of the Rift is along a vertical plane at the time that the Rift is initialized, and the trunk remains stationary during the task. These steps will be helpful for minimizing errors in Rift-based cervical spine kinematics measurement.

Conflict of interest statement

All authors declare that there is no proprietary, financial, professional or other personal interest of any nature or kind in any product, service or company that could be construed as influencing the position presented in this manuscript.

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